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RELIABILITY AND MAINTAINABILITY ANALYSIS OF FLUIDIC BACK-UP FLI--ETC(U)
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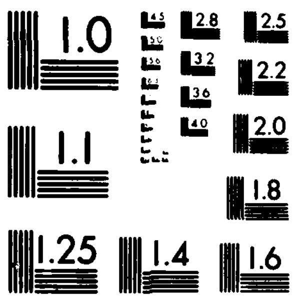
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RELIABILITY AND MAINTAINABILITY ANALYSIS OF FLUIDIC BACK-UP FLIGHT CONTROL SYSTEM AND COMPONENTS

SEPTEMBER 1981

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EXECUTIVE SUMMARY

BACKGROUND

High reliability in flight control systems is achieved by providing redundancy. There are two types of redundancy: "more of the same" redundancy - such as providing three or four flight control computers, and functional redundancy - providing a different type of system to do the same job. Those of the first kind are subject to common mode failures resulting, for example, from their common use of electricity. While fly-by-wire systems operate satisfactorily in known environments, some concern exists about the reliability of electronic flight controls in hazardous environments caused by nuclear blasts (EMP), lightning strikes, and energy fields associated with advanced systems. Fluidics provides a technologically distinct and redundant flight control system which is immune to electromagnetic interference and from loss of electric power. The feasibility of integrating a fluidic backup control channel with an advanced fly-by-wire flight control system has been demonstrated. This development will enhance the survivability of future aircraft.

RESULTS

The most important quality of a backup flight control system is that it must fly the aircraft when needed. Reliability must be very high even at the expense of flight performance capability, and the system must be insensitive to the failure modes of the primary system. For the system design described in

this report, it is estimated there is a 99.68% chance the backup flight controls will operate satisfactorily when needed. This probability assumes that prescribed standard maintenance is performed. It is estimated that the mean time between maintenance actions will be on the order of 37,000 engine operating hours. Half of these actions will be caused by the electric solenoid valve failing to switch in the fluidic backup.

FINDINGS

Although the reliability of fluidic devices constituting a fluidic backup flight control system (FBFCS) is believed to be high, very little failure rate data exists. Much of the reliability field data is based on experience from such fluidic systems as aircraft engine thrust reversers, approach power compensators, overspeed controllers and temperature sensing units. The experienced reliability of these particular devices is extremely high, but additional application data is needed to establish the reliability of fluidic systems in general.

Reliability Results of the reliability analysis indicate that contamination is the predominant failure mechanism in the FBFCS. Sources of contamination include ingestion of particles through component vents and seals, clogged filters and particles introduced during the manufacturing and production testing process. High reliability of fluidic devices for a FBFCS will depend upon using state-of-the-art design practices, proper filtration and manufacturing quality control practices comparable in effect to those of the electronics industry.

Maintainability Review of FMEA worksheets indicates that the standard hydraulic components of the servoactuator will require the majority of the required maintenance actions for the total flight control system. When a failure does occur within the FBFCS, replacement can be accomplished easily. During this analysis a general consideration of maintenance for each fluidic component was made and no maintenance problems were encountered except for detecting and locating a leak if the system is pneumatic.

RECOMMENDATIONS

- A detailed maintenance analysis should be accomplished after design details of the FBFCS are made available. The frequencies of occurrence as compiled in this report can be used for the maintenace analysis at the appropriate time.

- Currently, no specification exists for a FBFCS which establishes parameter limits for defining system or component failure. Another problem in quantifying the reliability of fluidic devices is the absence of standardized failure definitions. Additional specifications should be written to define and establish these functional requirements and parameter limits.

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1.0 INTRODUCTION TO THE ANALYSIS

An analytical technique called a Failure Mode and Effect Analysis (FMEA) is the usual approach to evaluating potential failure modes. There are two methods of performing an FMEA: the functional approach and the hardware approach. The functional approach is initiated by listing equipment functions at the system level. Failure modes contributing to nonconformance of desired functions are analyzed and failure effects determined. These effects become the failure modes at the next lower indenture level. This procedure is continued to lower fluidic indenture levels until all critical items are identified.

The other FMEA method is a hardware-oriented approach which is initiated by listing individual fluidic parts. Possible failure modes for each part are analyzed. Failure effects of the part itself and on other FBFCS elements are then determined. These effects become the failure modes at the next higher indenture level. This process is continued until the system (FBFCS) level is reached.

In the early development stage when a system has been conceived but detailed parts have not been decided upon, the functional approach is usually preferred. In the case of this FBFCS the overall system design has not been completed. However, considerable knowledge can be obtained and a baseline established for future analytic efforts by analyzing components which in all liklihood will be used in the FBFCS design. Therefore, the hardware-oriented FMEA approach was used for this particular analysis so that a more detailed parts analysis could be achieved. Procedures for conducting the FMEA and evaluating the

severity of each failure mode are included as Appendix A. Completed FMEA worksheets containing component failure modes, their effects, and failure rates are included as Appendix B.

This report summarizes potential failure modes of typical fluidic components as used in a FBFCS. An example of a FBFCS was identified and is shown in Figures 1 and 2. Failure rates of each failure mode are dependent upon various environmental factors such as shock, vibration, acceleration and working fluid temperature. They are also dependent upon design, material applications, manufacturing processes and required performance. Detailed failure rate data on these parameters is not available, and the typical Handbook method of assigning failure rates could not be used. Instead, a literature search was conducted, and failure rates were derived from published test data for similar components. Engineering analysis was used as necessary to complete the determination of failure rates. On the FMEA worksheets the following codes are used to indicate the source of the failure rate:

C Calculated
D Field Data
E Estimated
R Reference

Reports and documents used to identify failure modes and failure rates are listed in Appendix C.

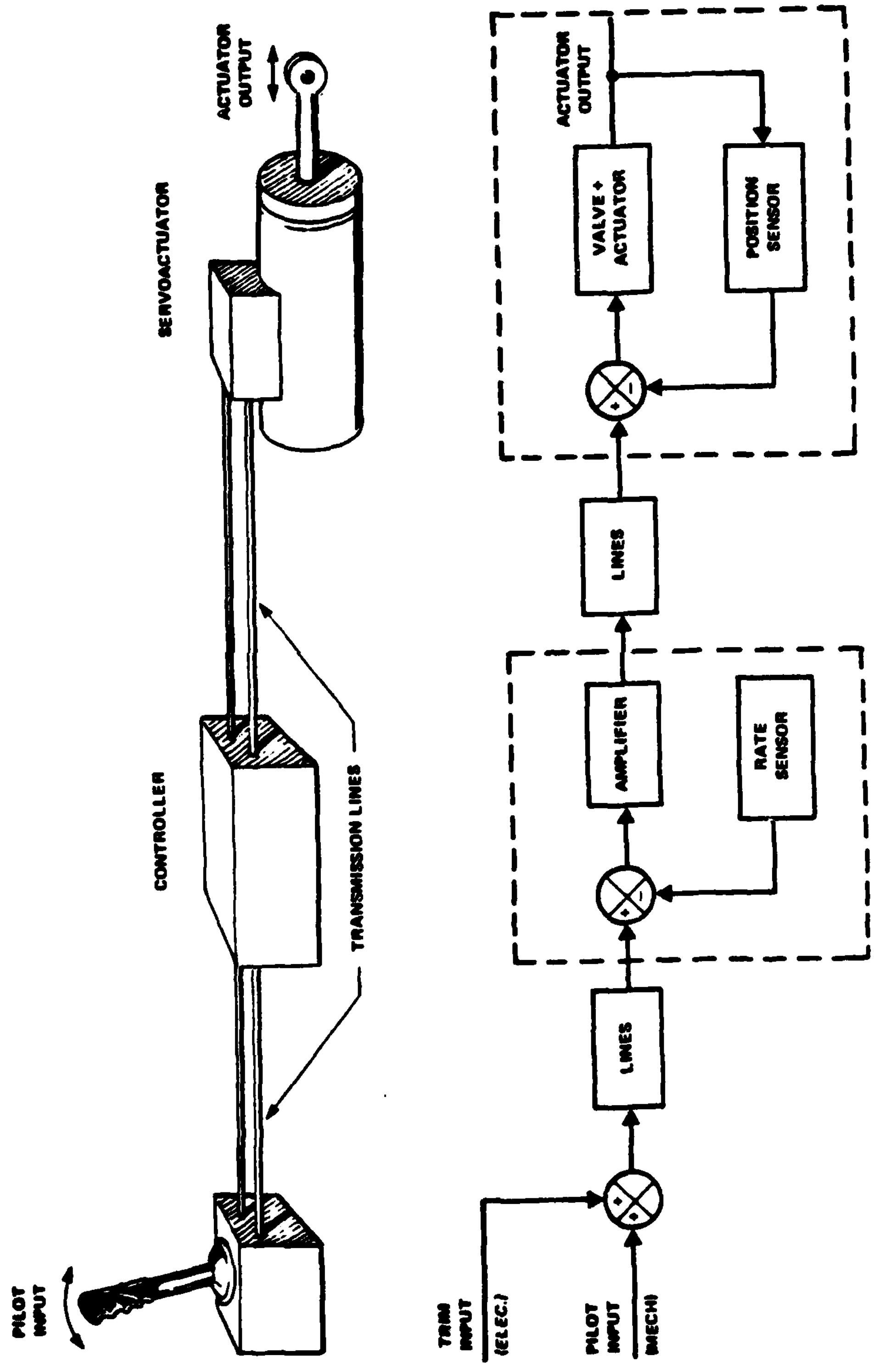


FIGURE 1 TYPICAL FLUIDIC BACKUP FLIGHT CONTROL SYSTEM

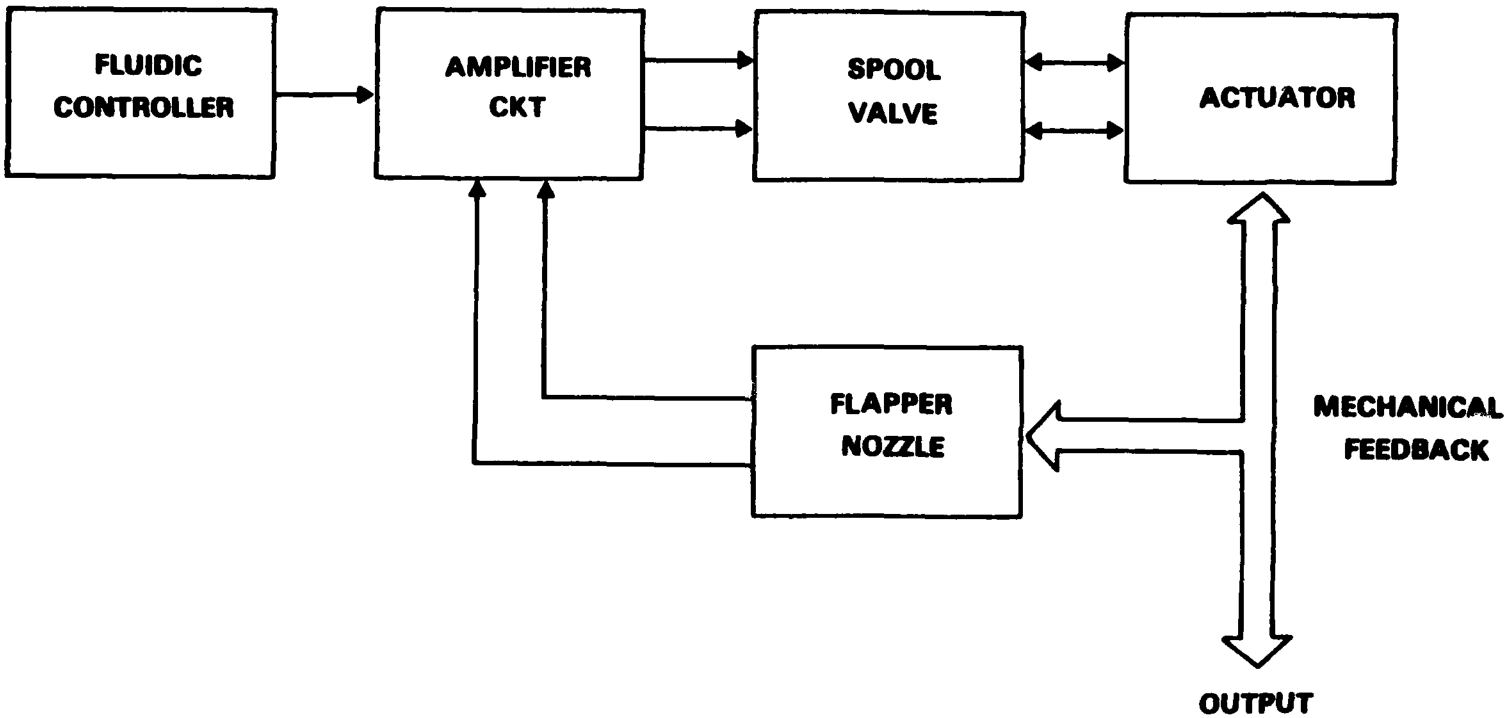


Figure 2. Typical Servoactuator for Fluidic Backup Flight Control System

2.0 FAILURE MODES OF FLUIDIC COMPONENTS

2.1 Pin Amplifier

A position-to-fluidic sensor is required on the FBFCS for transducing control stick and rudder motion. Most fluidic position transducers require a very small input motion although the motion they are measuring is relatively large. A pin amplifier used as a position sensor contains a small diameter pin placed in front of the receivers of a fluidic amplifier. With the pin located between the two receivers, the two output pressures are equal, resulting in a differential pressure output of zero. As the pin moves toward one receiver, interference of the jet occurs which reduces pressure in that receiver and increases pressure in the other. The net result is increased differential output pressure in relation to stick movement in one direction. When the pin is moved in the opposite direction, the change in receiver pressure is reversed providing a differential pressure of the opposite sense. Pin size is about the same as the receiver opening and maximum stroke is about one pin diameter. Gain of the pin amplifier is a function of supply pressure and loading.

Typical failure modes of the pin amplifier include clogging of the receiver openings with large particles, wear of the pin, and leakage. One of the results of these malfunctions is a drift of performance parameters such as null, linearity or scale factor. Failure modes of the motion reduction linkage must also be considered.

A review of available literature revealed contamination and clogging of fluidic elements as the predominant failure mode. These contaminants can be introduced into the assembly during the manufacturing process, or can enter into the fluidic system from the environment through vents and seals, or can be generated within the system or supply during normal operation.

Reliability of a fluidic device such as the pin amplifier depends upon the quantity of contaminants passing through individual elements and on the source of contamination. In turn the quantity of contaminants is dependent upon the environment, design, required performance, production techniques and the interaction of parameters.

Parameter drift in a position sensor caused by contamination is an example of a degradation type of failure mode. The other type of failure mode is complete cessation of intended system functions resulting in catastrophic failure. Catastrophic failure modes are rare in fluidic systems but were included in this analysis to aid in the precision of failure rate predictions.

2.2 Rate Sensors

Stabilization and rate damping of a FBFCS is achieved by inertial motion sensors. There are two basic approaches to fluidic rate sensors: the vortex rate sensor and the jet rate sensor. Research at Harry Diamond Labs (Reference No. 12) indicates that the jet rate sensor has better performance and lower flow requirements than the vortex rate sensor. Operation of the jet sensor is based on conservation of linear momentum. As the body is rotated about an axis normal to

the plane of the receivers, the jet is deflected relative to the receiver by an amount proportional to the rate of rotation and the time it takes the jet to traverse the distance between supply nozzle and receiver.

When using jet rate sensors for angular rotation rates, a common system configuration is to sum the stick or rudder input signal with rate feedback. Some of the potential failure modes of jet rate sensors include gain variations and null shift due to changes in temperature or Reynold's number. Gain variation with Reynold's number is an expected phenomenon of laminar devices; however, null output and null shift are effects that arise from imperfect manufacturing processes. As in the case of position sensors, rate sensors are sensitive to contamination resulting in leakage, clogging of vents and drifts of linearity, null and scale factor.

2.3 Accelerometer

A normal acceleration sensor may be used to sense statically unstable aircraft conditions. Fluidic accelerometers are usually constructed using some type of spring/mass system with a position pick-off. With the sensor in normal attitude, pin position can be adjusted for zero differential pressure output. Failure modes of an accelerometer are similar to those of position and rate sensors.

2.4 Signal Summing

In the controller of the FBFCS, inputs from pilot command, pilot trim, and angular rate are summed and then amplified to produce the desired output signal. The most common method of summing differential pressures uses a pair of linear

resistors connected to the input controls of a proportional amplifier. Output signals can exhibit droop if the sum of the input signals is sufficient to cause the amplifier output to saturate. Otherwise the only failure modes to be considered include those previously mentioned for other fluidic devices.

2.5 Transmission Lines

In a FBFCS, fluidic signals from the fluidic computer must be transmitted to an actuator at some remote location. Thin wall stainless steel tubing is generally used up to the pressure regulator within the supply. Nylon tubing is sometimes used for downstream supply and control pressures. Fittings, unions and elbows often consist of a molded polycarbonate plastic body enclosing aluminum tubing.

A review of test data showed that catastrophic failure of a fluid system as a result of ruptured supply or signal lines did not occur. This failure mode can be essentially eliminated by using proper design and packaging techniques. No attempt was made during this study to quantify the probability of supply line rupture as a result of battle damage.

Control signal transmission over long lines does not appear to be a problem if hydraulic or other oil is used as a medium. Signal fidelity in pneumatic circuits could be a problem, and further study of total system performance with pneumatic circuits is needed.

2.6 Servoactuator

Although the servoactuator contains nonfluidic devices including the spool valve and actuator, it is part of the total flight control system and was included in this analysis. Typical catastrophic mechanical failure modes exist for these devices. Servoactuators for a FBFCS usually consist of a torque motor, flapper nozzle, amplifier, spool valve, actuator, center lock mechanism and a solenoid valve. The torque motor accepts a signal from a fluid amplifier and produces a mechanical output which is proportional to the differental pressure from the fluid amplifier. There is a mechanical feedback connection from the output shaft to the nozzle end of the flapper-nozzle assembly. The other end of the flapper is driven by the torque motor. The reverse flow flapper nozzle acts as a mechanical to fluidic transducer for actuator position feedback.

The center lock mechanism causes the actuator shaft to center and be locked at the servoactuator null position when no fluidic signal is present. A solenoid valve directly mounted to the servoactuator remains closed so that when energized, fluid power will be applied to the flapper-nozzle, spool valve and center lock mechanism.

2.7 Power Supply

Power supplies for fluidic systems normally contain a filter assembly, pressure reducer, moisture separator, shut off valve, reservoir or plenum chamber. Reliability of a fluidic device and system is directly dependent upon the quantity of contaminants passing through individual elements as well as on the source of contamination. The designer of a filtration system is faced with a trade-off:

either short intervals between filter maintenance or underdesigning the particle size rating of the filter (thereby accepting a higher probability of component failure). Design of a filtration system must consider a prefilter sized to remove most of the particulate matter that normally would not pass through the smaller final stage filter.

Filtration design directly affects component reliability. Particle sizes, contaminant rates and filtration effectiveness must be taken into consideration when predicting reliability.

3.0 QUANTIFICATION OF FAILURE RATES

To calculate the effect of a failure mode on system performance, its probability of occurrence must be estimated. This report is intended to serve as a baseline for future tests and reliability predictions for a FBFCS. Failure modes as they occur during a testing program can be evaluated in terms of their expected probability of occurrence as discussed in this report.

Failure rates for this study were derived from the many available test reports and other technical papers on the subject of fluidic circuit reliability. Failure rates provided on the FMEA worksheets contain references to these publications which are listed in Appendix C. Some of the failure rates had to be estimated when no reference could be found, some failure rates were calculated and others were derived from field utilization data.

A summary of failure rates as entered on the worksheets is shown in Table I.

TABLE I

SUMMARY OF FBFCS FAILURE RATES

COMPONENT	FAILURE RATE IN FAILURES/10^6 HOURS
Pin Amplifier	.32
Transmission Line	.23
Rate Sensor	.20
Engage Solenoid	13.10

Amplifier (LPA), Qty = 5	1.00
Flapper Nozzle	6.10
Filter Assembly	6.00
	26.96

THREE MAJOR FAILURE CAUSES OF PURE FLUIDIC ELEMENTS	FAILURE RATE IN FAILURES/10^6 HOURS
CONTAMINATION	12.81
FATIGUE	1.83
SUDDEN PLUGGING OF VENT/NOZZLE	.013

SEVERITY LEVEL		FAILURE RATE IN FAILURES/10^6 HOURS
I	CATASTROPHIC	-
II	CRITICAL	.45
III	MAJOR	26.51
IV	MINOR	-
		26.96

From the above summary, the expected number of failures during a typical design life of 7000 hours can be computed as follows:

$$27 \times 10^{-6} \text{ failures/hour} \times 7000 \text{ hours} = 0.19 \text{ failures}$$

In other words, there is a good chance that during the 7000 hour design life of an aircraft there will be no failures of the FBFCS. The actual reliability of the FBFCS can be calculated by substituting failure rates from Table 1 into the exponential failure equation.

$$P_s = e^{-\lambda t}$$

where P_s = probability of success or reliability

λ = failure rate in failures per hour

t = time in hours

For the entire design life of an aircraft, reliability of the FBFCS is computed.

$$P_s = e^{-.19} = 82.7\%$$

Therefore, there is an 82.7% chance that no maintenance would ever be required on the FBFCS.

Only some of the failure modes are critical to mission success of the total flight control system. Using the same exponential failure law the probability that no critical failure mode will occur during the design life of the aircraft is as follows.

$$P_s = e^{-.45 \times 10^{-6} \times 7000} = 99.69\%$$

It should be noted that preventive maintenance and flight control checks are normally performed. If the FBFCS is verified to be operational prior to flight then the probability of it being operational during a typical two hour mission is as follows:

$$P_s = e^{-27 \times 10^{-6} \times 2} = 99.99\%$$

As noted in Table 1, most of the failures will be caused by contaminants. Because contamination is a relatively slow process, changes in flight performance are detectable prior to any catastrophic failure. The total failure rate is dependent on the time interval between maintenance actions. For example, if the FBFCS is cleaned and inspected every 500 engine hours, then the probability that the FBFCS will not be degraded by contaminants is estimated as follows:

$$P_s = e^{-12.8 \times 10^{-6} \times 500} = .9936$$

Assuming other failure modes are catastrophic, the probability that the FBFCS will not encounter a catastrophic failure is:

$$P_s = e^{-(27-12.8) \times 10^{-6} \times 7000} = .9054$$

Combining these probabilities provides a FBFCS reliability if the system is cleaned and inspected every 500 engine hours

$$P_s = .9936 \times .9054 = 89.61\%$$

Figure 3 provides other predictions of reliability as a function of hours between preventive maintenance.

The required frequency of corrective maintenance actions is estimated from failure rate of the FBFCS. Mean time between maintenance actions is the reciprocal of failure rate.

$$\text{MTBMA} = \frac{1}{\lambda} \qquad \frac{1 \times 10^{6}}{27} = 37{,}000 \text{ hours}$$

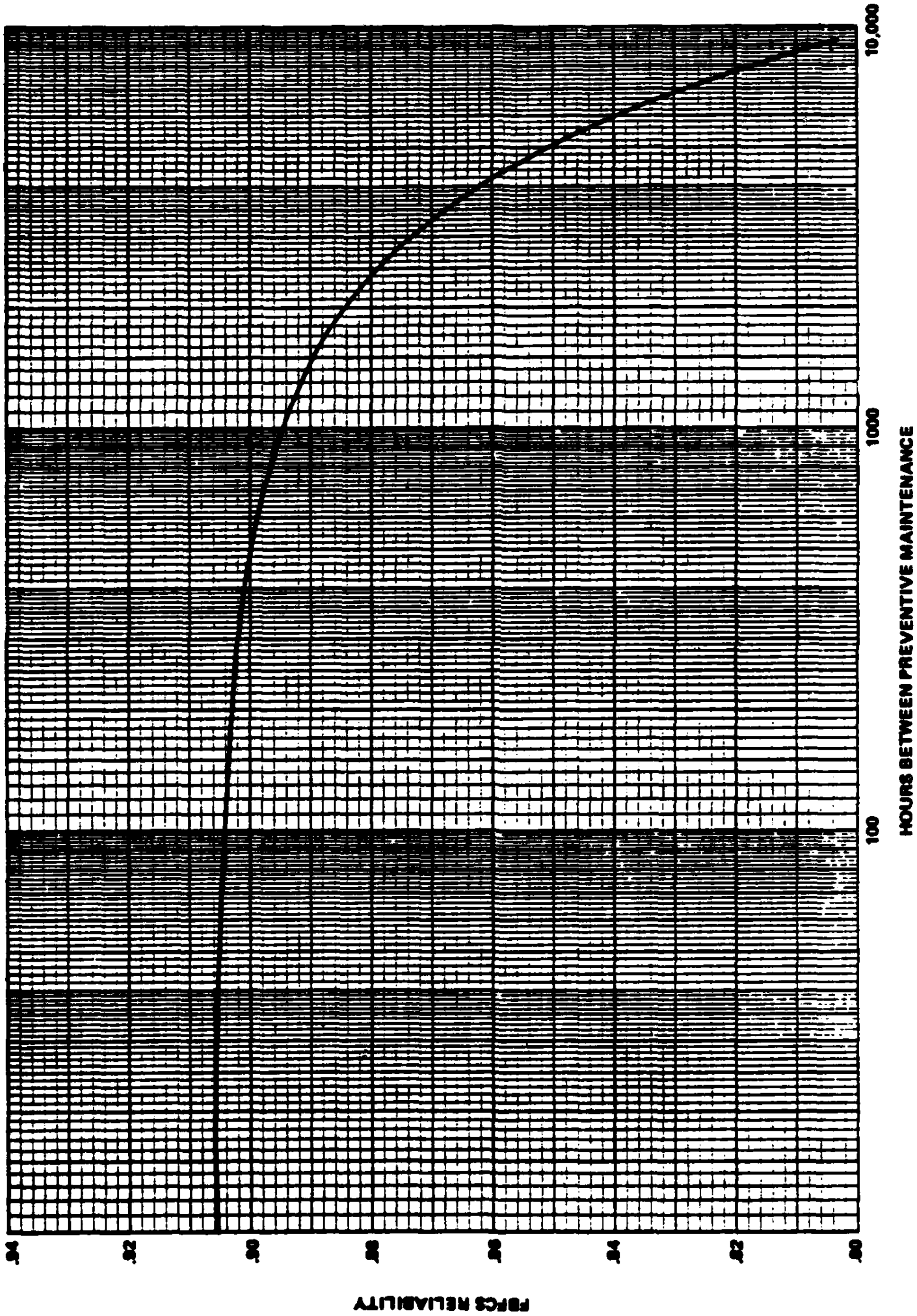


Figure 3. FLUIDIC SYSTEM RELIABILITY AS A FUNCTION OF HOURS BETWEEN MAINTENANCE

As seen from Table 1, contamination appears to be the chief concern in the performance of fluidic systems. The effects of contamination are very difficult to predict and even difficult to define with any precision. Some preliminary tests have been run to demonstrate these effects, and results indicate that the buildup of contaminants over a period of several years is sufficient to change the effective shape of a nozzle, produce a distorted jet, and eventually result in failure of the system.

One effect of contamination in a fluidic device is the buildup of deposits on the inside surfaces of the device. These contaminants may be carried into the device through the power supply or entrained from the environment through component vents. As the contaminate deposition process proceeds, geometry of the passages is changed. The contamination process is relatively slow, and the change in component performance is gradual with time.

Another effect of contamination is a sudden failure as large pieces of foreign matter completely block a nozzle or passage. These large particles consist of metal slivers and other pieces of material which may have broken away from the sharp edges of the sandwiched assemblies.

Seal erosion is another failure mode which must be considered in the evaluation of FBFCS reliability. Unfortunately, seal erosion is hard to predict and is dependent upon the basic system configuration. For example, in a low pressure liquid system a seal leak can be tolerated to some extent without adversely affecting component performance. However, in a pneumatic system even minute leaks can cause severe erosion in the seal layer which soon develops into a major leak and ultimate component failure.

Reliability prediction requires the consideration of performance characteristics with time and therefore a detailed knowledge of the contamination process. Additional work is required in this area to generate failure mode equations for predicting the probability of a failure occurring due to contamination. Figure 4 indicates some of the parameters to be included in such equations.

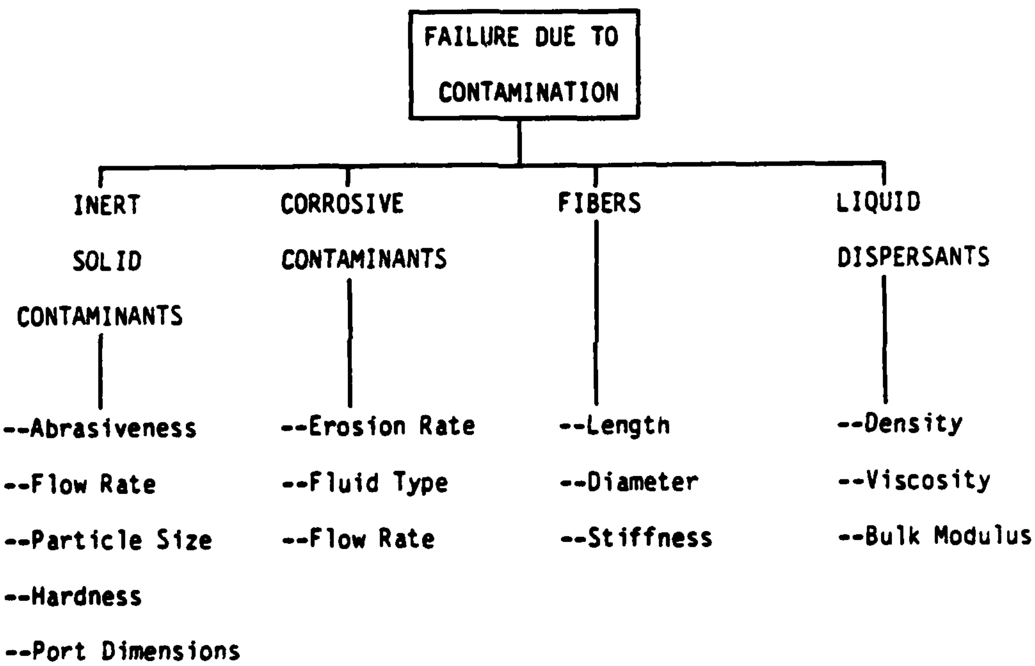


FIGURE 4 FAILURE MODE CONSIDERATIONS FOR CONTAMINATION

As an example of the use of these equations, the following equation for determining output flow, Q_F an amplifier or other fluidic device can be considered.

$$Q_F = \frac{\pi}{4} KD^2 C_D \sqrt{\frac{P_s}{\rho}} \qquad \text{REF 30}$$

where:

Q_F = Output flow, in^3/sec (m^3/sec)

D = Flapper fixed orifice diameter, in (m)

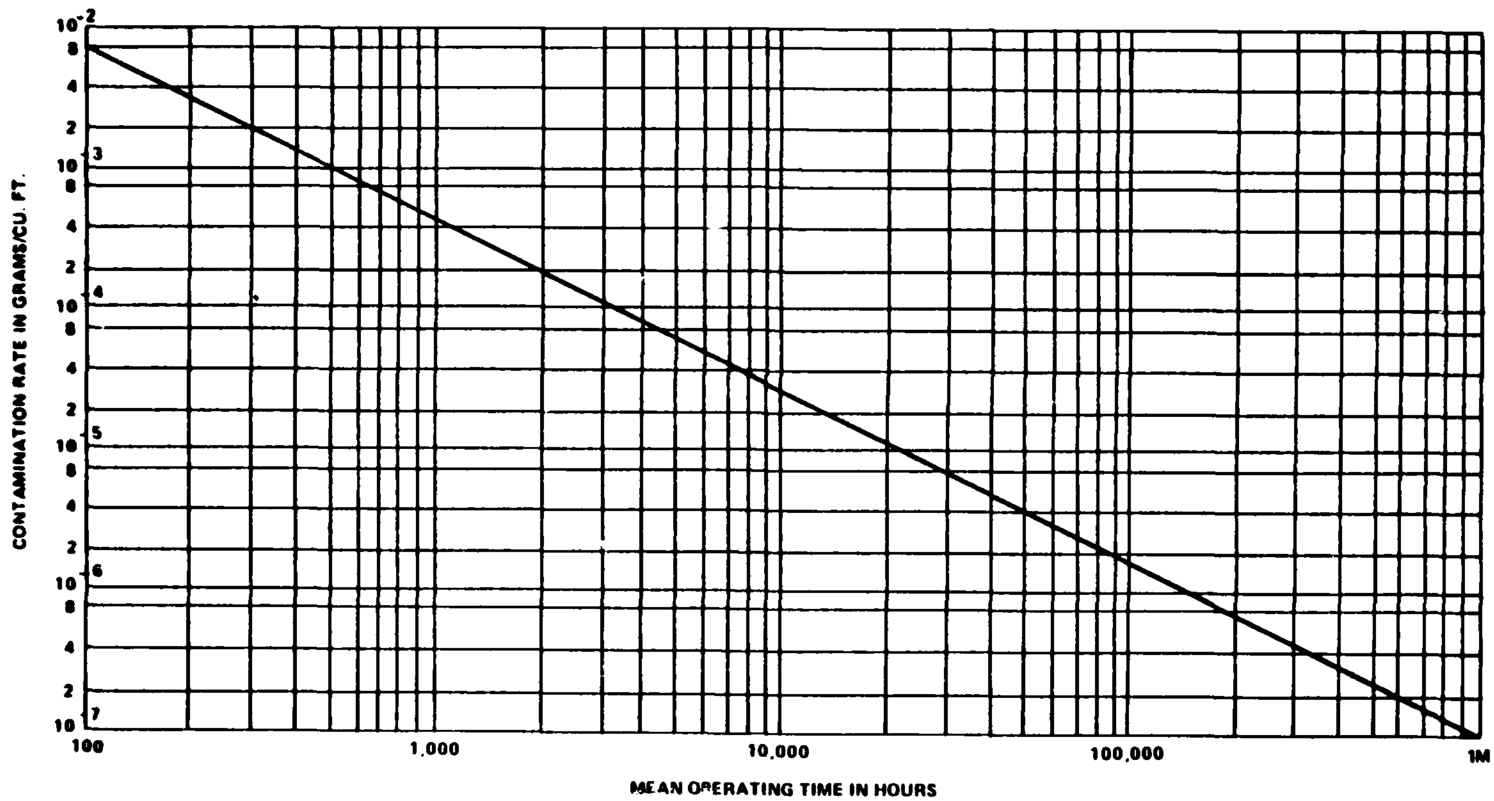
C_D = Hydraulic Amplifier (flapper) fixed orifice discharge coefficient

P_s = Supply pressure, psi (Pa)

ρ = Fluid density, lb/in^3 (Kg/m^3)

K = 61024 (1)

This equation can be used to determine flow rate. The density of particles in suspension can be estimated from test results or from analysis of the filtration system. Then Figure 5 can be used to determine the life of the fluidic component.



SOURCE: REFERENCE 12, "FLUIDIC RELIABILITY PROGRAM", McDONNELL ASTRONAUTICS CO.

FIGURE 5 MEAN OPERATING TIME OF FLUIDIC DEVICE AS A FUNCTION OF CONTAMINATION RATE

4.0 MAINTAINABILITY

A review of FMEA worksheets indicates the standard hydraulic components of the servoactuator will require the majority of the maintenance actions for the total flight control system. When a failure does occur within the FBFCS, replacement can be accomplished quite rapidly. During this analysis a general consideration of maintenance for each fluidic component was made and no maintenance problems were encountered except detecting and locating a leak if the system is pneumatic.

Most of the fluidic failure modes are caused by contamination (which is a slow process) and as a result performance deterioration will occur gradually. Means of evaluating FBFCS performance must be accomplished as part of the routine maintenance of the flight control system.

A detailed maintenance analysis should be accomplished after design details of the FBFCS are made available. The frequencies of occurrence as compiled in this report can be used for the maintenance analysis at the appropriate time.

5.0 CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

The primary mode of failure for fluidic circuits appears to be contamination. Effects of contamination are difficult to evaluate and depend upon the type of contaminant such as inert solid contaminants, liquid dispersents, fibers, and corrosive contaminants. Further work is needed to develop failure rate equations for each of the contaminant-related failure modes identified in this report. These equations can be used to determine mean time between failure of a fluidic device and must include supply pressure, nozzle area, circuit material and contaminant rate, size and hardness.

Contamination plays a major role in determining field reliability and maintainability of a FBFCS. Clogging of supply nozzles and control ports, and parameter drift are serious failure modes affecting total FBFCS reliability, but their occurrence probability is very small. Maintainability of the FBFCS will be determined by the capability to measure degraded performance.

The most hazardous failure modes identified are those causing an actuator hardover position. Fortunately, the probability of these failure modes occurring is very low.

RECOMMENDATIONS

Specifications which define the total FBFCS and which establish functional requirements and parameter limits should be developed for setting design standards and establishing ground rules for further analysis.

APPENDIX A

PROCEDURE FOR IDENTIFYING FAILURE MODES OF A FLUIDIC SYSTEM

FAILURE MODE IDENTIFICATION
HARDWARE APPROACH

1. SCOPE

1.1 Purpose. The basic purpose of this procedure is to determine possible modes of failure within an equipment, the effect of each mode of failure on the overall equipment or portion thereof and those sensitive equipment items which mandate a stress analysis. This procedure establishes the requirement for identifying critical failure modes using the hardware approach. A detailed analysis using the hardware approach is initiated by listing individual equipment items. Possible failure modes for each equipment item are then analyzed. Failure effects on performance of the item itself and on other hardware system elements are then determined and become the failure modes at the next higher indenture level.

1.2 Application. The hardware approach is a rigorous method of identifying failure modes and is normally used whenever the hardware items can be identified from engineering drawings. While the hardware approach is normally utilized in a part level up fashion, it can be initiated at almost any indenture level and can proceed in either direction.

2. PROCEDURE FOR COMPLETING WORKSHEETS

Each analysis will require specific worksheet forms to be designed for information contained in the following paragraphs.

2.1 Item identification. The first worksheet entry contains the hardware item under analysis. Assembly drawing symbols, drawing numbers or other coding designations may be used to identify the item.

2.11 Identification number. When entering the item identification on the worksheet, a serial number or other reference designation is assigned for traceability and complete visibility of each failure mode in relation to the hardware system.

2.12 Mission/operational phase. A concise statement of the mission or equipment operational phase as defined in the equipment item description is listed.

2.2 Function. A concise statement of the function performed by the hardware item is listed.

2.3 Failure mode. By examining the outputs of all the items and output functions identified in the applicable reliability model, all potential failure modes are identified and described . Failure modes of the individual hardware item are postulated on the basis of the stated requirements contained in the narrative. The following are typical failure modes and are the minimum that shall be considered in the analysis. Other unique failure modes are considered as applicable.

a. Premature operation.

b. Failure to operate at a prescribed time.

c. Failure to cease operation at a prescribed time.

d. Loss of output or failure during operation.

e. Degraded output or operational capability.

f. Unstable output or operation.

2.4 Failure cause. The possible causes associated with each postulated failure mode are identified and described. The causes of each failure mode are identified in order to estimate its probability of occurrence, uncover secondary effects and formulate recommended corrective action. A failure mode can have more than one cause, and all potential independent causes for each failure mode are identified and described. The failure causes within the adjacent indenture levels are considered when conducting a second indenture level analysis.

2.5 Failure effect. The consequences of each assumed failure mode on item operation, function, or status are identified, evaluated, classified, and recorded. Failure effects focus on the specific element being analyzed which is affected by the failure under consideration. A failure effect also impacts the next higher indenture level under analysis. Therefore, both a "local" effect and an "end" effect should be evaluated. Failure effects analysis also considers maintenance, personnel and mission objectives.

2.51 Local effects. Local effects concentrate specifically on the effect of the failure mode on the operation and function of the item under consideration. The consequences of each postulated failure on the output of the item are described along with the secondary effects. The purpose of defining the local effects is to provide a base for judgment when evaluating existing compensating provisions or formulating recommended corrective actions. it should be noted that in certain instances there may not be a "local" effect beyond the description of the failure mode itself.

2.52 End effect. The end effect analysis evaluates and defines the effect of the postulated failure on the operation, function, and status of the next higher indenture level. The end effect described may be the result of a double failure. For example, failure of a safety device results in a catastrophic end effect only in the event that both the safety device fails and the prime function goes beyond the limit for which the safety device is set.

2.6 Failure detection method. A description of the methods by which occurrence of the failure mode is detected by the operator is next recorded. Failure modes other than the one being considered which present an identical indication to the operator are analyzed and listed. Redundant items need to be evaluated to determine failure detection during a mission.

2.7 Compensating provisions. Any internal compensating provision at any indenture level that either circumvents or mitigates the effect of the postulated failure is identified and evaluated. This step is required to record the true behavior of the item in the presence of an internal malfunction. Compensating provisions include: redundant items which allow continued and safe operation if one or more items fail, alternate modes of operation, safety or relief devices such as a monitoring or alarm provision or any other means which permits effective operation or limits damage in the presence of a failure. Evaluation of redundant items include the loss probability of both prime and backup items.

2.8 Level of severity. The level of severity is a classification assigned to each failure mode according to its effect on the operational function of the item. The effect on the functional condition of the item caused by the loss or

degradation of output is identified so that the failure mode effect will be properly categorized into one of the levels described below. The level of severity selected shall be the most severe level of an item regardless of whether a less severe classification is also applicable.

Classification of level of severity is established as follows:

2.81 Level I, catastrophic. Characterized by any of the following conditions:

(1) Severe reduction in mission capability.

(2) Complete functional output loss of the item at the highest indenture level.

(3) Other item failure requiring depot maintenance repair.

(4) Loss of life.

2.82 Level II, critical. Characterized by any of the following conditions:

(1) Some degradation in mission capability.

(2) Severe reduction in functional output of the item at the highest indenture level.

(3) Other item failure that cannot be repaired immediately within the capability of organizational level maintenance.

(4) Personal injury.

2.83 Level III, major. Characterized by any of the following conditions:

(1) Negligible effect on mission capability.

(2) Degradation in functional output of the item at highest indenture level.

(3) Other item failure that can be repaired immediately within the capability of organizational level maintenance.

2.84 Level IV, minor. Characterized by any of the following conditions:

(1) No effect on mission capability.

(2) Negligible effect on functional output of the item at highest indenture level.

(3) Other item degradation that can be repaired by performing "adjustment" maintenance.

3.0 CRITICALITY ANALYSIS AND THE QUANTITATIVE APPROACH

3.1 Purpose. The basic objective of the Criticality Analysis (CA) is to rank each potential failure according to the combined influence of failure effect severity and loss frequency. This procedure establishes the requirements for conducting a CA using a quantitative approach. The quantitative approach computes loss frequency in terms of failure rate for each failure mode. The quantitative approach also considers application and environmental factors.

3.2 Application. The quantitative approach to conducting a CA is normally used whenever a failure rate data base is available for the analysis. A quantitative analysis is usually performed in conjunction with other reliability analyses such as a reliability prediction or maintainability analysis that utilizes the same failure rate determinations.

3.3 PROCEDURES FOR USING THE WORKSHEETS

Worksheets need to be devised for the particular equipment item being analyzed. Recommended worksheet entries include: a) The basic failure rate of the

hardware item or function, b) The fraction of the part failure rate attributable to the critical failure mode being considered, and c) A conditional probability factor for the failure effect occurring, given that the failure mode has occurred.

3.31 Part failure rate (λp). The first failure rate column contains the failure rate of the item in its operational mode and environment. Where appropriate, application factors (K_A) and environmental factors (K_E) shall first be applied to adjust for the difference between operating stresses of the generic failure rate data and the operating stresses under which the item is going to be used. Values for K_A and K_E may be listed on the worksheet if desirable for future analysis use. Equipment duty cycles need to be considered in the application of failure rates.

3.32 Failure rate data. If available, reliability data resulting from tests run on the specific item shall be used with tests performed under the identical conditions of use. If handbooks or other source material are used to determine failure rates, K_A and K_E shall be considered and applied whenever possible. When valid failure rate data cannot be obtained, failure rates shall be derived from operational experience and tests which have been performed on similar equipment operating under conditions similar to the expected application and environment. When using the hardware approach to identify initial failure modes, failure rates are listed for the item identified. If the functional approach is being used to identify critical failure modes, failure mode descriptions are expressed as functions. In this case it will be necessary to derive failure rates for the equipment items listed as failure cause.

3.33 Failure mode ratio (α). The fraction of the part failure rate (λp) related to the particular failure mode under consideration shall be evaluated and recorded. If all potential failure modes of a particular item are listed for the hardware approach, the sum of the α values for that item will equal one. Individual failure mode multipliers are derived from test reports and operational data or analysis of the item's function in the equipment. If no operational data are available, values of α can be approximated by engineering analysis of item functions.

3.34 Probability of failure effect (β). The conditional probability that the critical failure effect occurs, given that the failure mode has occurred, are listed. The β values are based upon engineering analysis of the equipment and are obtained using the following guidelines:

Effect	Probability of Occurrence, (β)
Actual	$\beta = 1.00$
Probable loss	$0.10 < \beta < 1.00$
Possible loss	$0 < \beta \leq 0.10$
No effect	$\beta = 0$

3.35 <u>Operational failure rate (λ_o)</u>. The operational failure rate is the product of λ_p, α and β. The resulting failure rate is the number of times the listed failure effect is expected to occur per mission hour or any other time base selected. This failure rate may be converted to probability of occurrence if desired by using the mission time or other time interval as discussed in the narrative section. These failure rates are used in conjunction with the severity levels to develop a criticality matrix.

APPENDIX B

FAILURE MODE AND EFFECT ANALYSIS WORKSHEETS

FAILURE MODE AND EFFECT ANALYSIS

COMPILED BY W/-'
DATE 8/10/81
SHEET 1 of 9

NOTE: FAILURE RATES IN FAILURES/10^6 HR.

ITEM IDENTIFICATION	FUNCTION	ID NO.	FAILURE MODE	FAILURE CAUSES	FAILURE EFFECT: LOCAL EFFECTS	FAILURE EFFECT: END EFFECT	FAILURE DETECTION METHOD	COMPENSATING PROVISIONS	SEVERITY LEVEL	LOSS FREQUENCY: λ_p	α	β	λ_m	DATA CODE	REMARKS
PIN AMPLIFIER	Provides position to Fluidic Translation and Amplification	1.1	slow or moderate change in null, linearity or scale factor (gain) beyond tolerance as follows: linearity: ›10% scale factor: ›20% null: ›30% (percent of range)	- change in passage geometry from contamination build-up, erosion of sharp edges or wear in interaction region.	excessive hysteresis, change in output vs stick/rudder pedal movement	change in system response (oversensitive or sluggish flight control)	change in null position at system checkout or FBFCS performance sensitivity during flight	Feedback circuits; gradual deterioration	III	2.0 (R)	.4	.1	.08	1 11 25 26 27	1
				- contamination of input slots							.2	.1	.04		
				- particles introduced during assembly process							.2	.1	.04		
				- Separation of bonded joint permitting leakage							.1	.1	.02		
				- wear of pin							.1	.1	.02		
		1.2	Loss of Amplifier output	- sudden plugging of nozzle, passage or control port by large piece of contaminant	loss of stick/rudder pedal signal to controller	could result in complete loss of roll, yaw or pitch control with servo-actuator in null position	FBFCS performance check		II	.01 (E)	.8	.1	.001	30	
				- fatigue failure of a thin section due to moderate stress margin or manufacturing flaw							.2	.1	-		
		1.3	abrupt/erratic change in null or response	- disconnected/broken or jammed linkage causing eratic movement of pin	gain/scale factor change or output port goes into saturation	possible loss of flight control capability	FBFCS performance check	backup system	II	1.2 (C)	1.0	0.1	.12		
													.32		
				- side loading on linkage											

1. High level of contaminant could produce category II failure

FAILURE MODE AND EFFECT ANALYSIS

COMPILED BY WHZ
DATE 8/12/81
SHEET 2 of 9

NOTE: FAILURE RATES IN FAILURES/10^6 HR.

ITEM IDENTIFICATION	FUNCTION	I.D. NO.	FAILURE MODE	FAILURE CAUSES	FAILURE EFFECT: LOCAL EFFECTS	FAILURE EFFECT: END EFFECT	FAILURE DETECTION METHOD	COMPENSATING PROVISIONS	SEVERITY LEVEL	LOSS FREQUENCY: λ_p	LOSS FREQUENCY: α	LOSS FREQUENCY: β	LOSS FREQUENCY: λ_e	DATA CODE	REMARKS
TRANSMISSION LINE & CONNECTIONS	Provide Fluidic Circuit Continuity	2.1	Partial blockage of line	contamination build-up	high resistance to flow; pressure drop	Possible Degradation of FBFCS response	system performance check or FBFCS sensitivity change during flight	feedback circuits; gradual degradation	III	.1 (E)	1.0	.1	.01		1
		2.2	Complete blockage of line	large particle	pressure loss	loss of FBFCS function- servo-actuator goes to null position	system performance check	backup system	II	.1 (E)	1.0	.1	.01		1
		2.3	Fractured/broken line	fatigue	pressure loss	loss of FBFCS function- servo-actuator goes to null position	system performance check	backup system	II	.1 (R)	1.0	.1	.01	26	2
		2.4	External leakage at bend or fitting	corrosion, fluid turbulance	local pressure drop	could result in loss of FBFCS function	system performance check	backup system	II	.01 (E)	1.0	.1	.001		
		2.5	Interconnection fracture	fatigue	pressure loss	could result in loss of FBFCS function	system performance check	backup system	II	2.0 (R)	1.0	.1	.2	25 1 27	3
													.23		

1. F.R. = .001/ft
2. 10 lines
3. F.R. = .02/connection

FAILURE MODE AND EFFECT ANALYSIS

COMPILED BY ✓
DATE 8/13/81
SHEET 3 of 9

NOTE: FAILURE RATES IN FAILURES/10^6 HR.

ITEM IDENTIFICATION	FUNCTION	I.D. NO.	FAILURE MODE	FAILURE CAUSES	FAILURE EFFECT: LOCAL EFFECTS	FAILURE EFFECT: END EFFECT	FAILURE DETECTION METHOD	COMPENSATING PROVISIONS	SEVERITY LEVEL	LOSS FREQUENCY: λ_p	LOSS FREQUENCY: α	LOSS FREQUENCY: β	LOSS FREQUENCY: λ_o	DATA CODE	REMARKS
Rate Sensor Package (includes two fluidic amplifiers)	Provide stabilization and rate damping	3.1	slow or moderate change in null, linearity or scale factor (gain) beyond tolerance as follows:	- excessive change in passage geometry from contamination build-up or erosion of sharp edges.	excessive hysteresis, change in output characteristics	change in FBFCS response characteristics	system performance checks or gradual change in flight control characteristics	gradual change in characteristics of backup system	III	2.0 (R)	.4	.1	.08	1 11 25 26 27	
			linearity: >10% scale factor: 20% null: 30% (percent of range)	- excessive force on pick-off blade							.1	.1	.02		
				- delamination due to improper bonding							.1	.1	.02		
				- wear in interaction region							.3	.1	.06		
				- thermal distortion							.1	.1	.02		
		3.2	loss of rate sensor output	- sudden plugging of nozzle, passage or control port by large piece of contaminant	loss of rate signal to controller	insufficient FBFCS damping	system performance checks	backup system	II	.01 (E)	.8	.1	.001	30	
				- fatigue failure of thin walled section							.2	.1	-		
													.20		

FAILURE MODE AND EFFECT ANALYSIS

COMPILED BY ___ WHS
DATE ___ 8/19/81
SHEET ___ 4 of 9

NOTE: FAILURE RATES IN FAILURES/10^6 HR.

ITEM IDENTIFICATION	FUNCTION	I.D. NO.	FAILURE MODE	FAILURE CAUSES	FAILURE EFFECT: LOCAL EFFECTS	FAILURE EFFECT: END EFFECT	FAILURE DETECTION METHOD	COMPENSATING PROVISIONS	SEVERITY LEVEL	LOSS FREQUENCY: λ_p	LOSS FREQUENCY: α	LOSS FREQUENCY: β	LOSS FREQUENCY: λ_o	DATA CODE	REMARKS
ENGAGE SOLENOID/VALVE ASSEMBLY	Disengages the fluidic backup control when engaged	4.11	Worn or damaged poppet/seat	Contaminants; fatigue; overheating	Poppet does not seat properly; internal leakage	Does not disengage FBFCS completely	Deteriorated primary system performance	-	III	14 (E)	1.0	.1	1.4		
		4.12	Broken/weak return spring	Fatigue	Low or erratic pressure drop; valve may bind; internal leakage	Does not disengage FBFCS completely	Deteriorated primary system performance	-	III	1 (E)	1.0	.1	0.1		
		4.13	Sticking valve piston	Contaminants	Low or erratic pressure drop, internal leakage	Does not disengage FBFCS completely	Deteriorated primary system performance	-	III	30 (E)	1.0	.1	3.0		
		4.14	Restricted orifice; dirt, chip, burr holding valve open	Contaminants	Internal leakage	Does not disengage FBFCS completely	Deteriorated primary system performance	-	III	5 (E)	1.0	.1	0.5		
		4.15	Seal/packing failure	Aging	Internal leakage, reduction in output force	Could cause intermittant system response	System performance check	-	III	6 (E)	1.0	.1	0.6		
		4.16	Cracked housing	Fatigue, vibration	External leakage	Loss of system fluid; possible loss of flight control capability	System performance check	Backup system	III	.003 (E)	1.0	.1	-		
		4.17	Open winding on solenoid coil	Shorted windings	Coil does not energize	FBFCS does not disengage	Deteriorated primary system performance	-	III	50 (R)	1.0	.1	5.0		
		4.18	Shorted winding on solenoid coil	Insulation breakdown	Coil does not energize	FBFCS does not disengage	Deteriorated primary system performance	-	III	25 (E)	1.0	.1	2.5 / 13.1		

FAILURE MODE AND EFFECT ANALYSIS

COMPILED BY ______

DATE 8/19/81

SHEET 5 of 9

NOTE: FAILURE RATES IN FAILURES/10[6] HR.

ITEM IDENTIFICATION	FUNCTION	ID NO.	FAILURE MODE	FAILURE CAUSES	FAILURE EFFECT: LOCAL EFFECTS	FAILURE EFFECT: END EFFECT	FAILURE DETECTION METHOD	COMPENSATING PROVISIONS	SEVERITY LEVEL	LOSS FREQUENCY: λ_p	LOSS FREQUENCY: α	LOSS FREQUENCY: β	LOSS FREQUENCY: λ_a	DATA CODE	REMARKS
AMPLIFIER	Provide Amplified controller signal to servo-actuator	4.21	Slow or Moderate Change in null, linearity or scale factor (gain) beyond tolerance	- Change in passage geometry from contamination build-up, erosion of sharp edges or wear in interaction region.	Excessive hysterisis, change in signal input to servo-actuator	deterioration in system response characteristics	change in system characteristics during system checkout	Gradual Deterioration	III	2.0 (R)	.4	.1	.08	28	
				- Contamination of input slots							.2	.1	.04		
				- Particles introduced during assembly process.							.2	.1	.04		
				- Separation of bonded joint permitting leakage.							.2	.1	.04		
		4.22	Loss of amplifier output	- Sudden plugging of nozzle, passage or control port by large piece of contaminant	Loss of signal input to servo-actuator	Could result in complete loss of roll, yaw or pitch control with servo-actuator in null position	System Performance	Back-up System	II	.01 (E)	.8	.1	.001		
				- Fatigue Failure of a thin section due to moderate stress margin or manufacturing flaw.							.2	.1	--		
													0.2		

FAILURE MODE AND EFFECT ANALYSIS

COMPILED BY ______
DATE 8/20/81
SHEET 6 of 9

NOTE: FAILURE RATES IN FAILURES/10^6 HR.

ITEM IDENTIFICATION	FUNCTION	I.D. NO.	FAILURE MODE	FAILURE CAUSES	FAILURE EFFECT: LOCAL EFFECTS	FAILURE EFFECT: END EFFECT	FAILURE DETECTION METHOD	COMPENSATING PROVISIONS	SEVERITY LEVEL	LOSS FREQUENCY: λ_p	LOSS FREQUENCY: α	LOSS FREQUENCY: β	LOSS FREQUENCY: λ_o	DATA CODE	REMARKS
SERVO ACTUATOR FLAPPER NOZZLE	Provide mechanical to fluidic conversion for actuator position feedback	4.31	Low gain	contamination	gain change	noisy operation, change in operating characteristics	system performance check or flight handling change in performance	gradual degradation back-up flight control system	III	30 (R)	1.0	.1	3.0	28	
		4.32	Nozzle bias	contamination	performance degradation	degradation of performance - command offset	system performance checks or flight handling change in performance	gradual degradation back-up flight control system	III	30 (R)	1.0	.1	3.0	28	
		4.33	orifice blockage	large piece of contaminant	loss of fluidic output to amplifier	possible actuator hardover	system performance checks	back-up flight system	II	.01 (R)	1.0	.1	.001	30	
		4.34	damaged flapper assembly	fatigue, mechanical overdrive	erratic output to amplifier	possible loss of flight control capability	system performance checks	back-up flight system	II	1 (E)	1.0	.1	.1		
													6.1		

FAILURE MODE AND EFFECT ANALYSIS

COMPILED BY MHS
DATE 8/17/81
SHEET 7 of 9

NOTE: FAILURE RATES IN FAILURES/10^6 HR

ITEM IDENTIFICATION	FUNCTION	I.D. NO.	FAILURE MODE	FAILURE CAUSES	FAILURE EFFECT		FAILURE DETECTION METHOD	COMPENSATING PROVISIONS	SEVERITY LEVEL	LOSS FREQUENCY				DATA CODE	REMARKS
					LOCAL EFFECTS	END EFFECT				λ_p	α	β	λ_o		
SERVO-ACUTATOR SPOOL VALVE	Control extension of actuator	4.41	Damaged rod seal in servo cylinder	Extrusion and nibbling spiral cut; abrasion;	external leakage	actuator positioning error	System Performance check	--	III	354 (D)	.30	.7	74.3		
		4.42	Scratched/deformed piston	Fatigue; maintenance action	internal leakage	actuator positioning error	System Performance check	--	III		.08	.6	17.0		
		4.43	Damaged centering spring	Fatigue; damaged spring guide	positioning error, poor response	Flight control positioning instability	System Performance check	--	II		.05	.7	12.4		
		4.44	Crack in cylinder/housing/connector	Fatigue; external shock, vibration	external leakage	loss of system fluid and loss of flight control capability	Flight Performance check	--	I		.03	.8	8.5		
		4.45	Clogged supply/return manifold	large piece of contaminant	loss of fluid output	erratic flight control performance	Flight Performance check	--	II		.08	.8	22.7		
		4.46	Damaged packing/gland	extrusion and nibbling; abrasion; cracking; hardening	external leakage	loss of system fluid; loss of flight control capability	Flight Performance check	--	I		.15	.8	42.5		
		4.47	Worn Barrel Surface	Fatigue	internal leakage	Possible loss of flight control capability	Flight Performance check	--	II		.18	.8	51.0		
		4.48	Jamming of spool	Large contaminant particle	Parameter offset	loss of flight control capability	Flight Performance check	--	I		.13	.7	32.2	28	
													260.6		

FAILURE MODE AND EFFECT ANALYSIS

COMPILED BY MWS
DATE 8/21/81
SHEET 8 of 9

NOTE: FAILURE RATES IN FAILURES/10^6 HR.

ITEM IDENTIFICATION	FUNCTION	I.D. NO.	FAILURE MODE	FAILURE CAUSES	FAILURE EFFECT: LOCAL EFFECTS	FAILURE EFFECT: END EFFECT	FAILURE DETECTION METHOD	COMPENSATING PROVISIONS	SEVERITY LEVEL	LOSS FREQUENCY: λ_p	LOSS FREQUENCY: α	LOSS FREQUENCY: β	LOSS FREQUENCY: λ_o	DATA CODE	REMARKS
ACTUATOR	Convert Fluid Energy with linear mechanical force	4.51	Damaged rod seal in actuator cylinder	Extension and nibbling; spiral cut; abrasion; installation damage	Internal leakage	loss of actuator force	System Performance check	Tandem Cylinder; Back-up seals	I	694 (D)	.4	.2	55.5		
		4.52	Bent actuator piston rod	Fatigue; external force	Cylinder binding	Rough extension/contraction	System Performance Check	Tandem Cylinder	II		.1	.7	48.6		
		4.53	Seal/packing failure	Contaminants, extrusion and nibbling; abrasion, cracking, hardening	External leakage	Possible entry of contaminants possible loss of actuator force	System Performance Check	--	II		.2	.2	27.8		
		4.54	Crack in cylinder/cap/connector	Fatigue; external shock vibration	External leakage	Loss of system fluid	System Performance Check	--	I		.05	.7	24.3		
		4.58	Scratched/deformed actuator piston	Fatigue; maintenance action	Internal Leakage	Reduction in Actuator Force	System Performance Check	Tandem Cylinder	II		.25	.5	86.8		
													243.0		

FAILURE MODE AND EFFECT ANALYSIS

COMPILED BY: WHS
DATE: 8/21/81
SHEET: 9 of 9

NOTE: FAILURE RATES IN FAILURES/10^6 HR

ITEM IDENTIFICATION	FUNCTION	I.D. NO.	FAILURE MODE	FAILURE CAUSES	FAILURE EFFECT: LOCAL EFFECTS	FAILURE EFFECT: END EFFECT	FAILURE DETECTION METHOD	COMPENSATING PROVISIONS	SEVERITY LEVEL	LOSS FREQUENCY: λ_p	LOSS FREQUENCY: α	LOSS FREQUENCY: β	LOSS FREQUENCY: λ_o	DATA CODE	REMARKS
POWER SUPPLY FILTER	Provide clean fluid for FBFCS components	5.1	Filter clogged prematurely	- Excessive no. contaminants prior to element change	Increase in pressure across filter	Bypass of contaminants create failure modes downstream	Filter element maintenance check	-	III	60 (R)	.6	.1	3.6		1 27 24
				- Loose particles generated during assembly process or bonding operation							.3		1.8		
				- Edgewise passage of contaminants fibers through filter							.1		0.6 6.0		

APPENDIX C

BIBLIOGRAPHY

BIBLIOGRAPHY OF FLUIDIC RELIABILITY

1. "Fluidic Reliability", H. Ogren, E. Peterson and D. Bengston, Honeywell Inc., Minneapolis, Minnesota; prepared for U.S. Army Aviation Material Laboratories, Fort Eustis, VA., USAAVLABS Technical Report 68-36, June, 1968

A feasibility-model hydraulic single-axis Stability Augmentation System (SAS) was tested under conditions simulating UH-1B helicopter flights. A total of 15 each of the components were life tested under various environmental conditions. The SAS test was completed with no failures. Report discusses testing procedures and possible wearout failure modes.

2. "Procedure for Obtaining Fluidic Amplifier Reliability Data", J. Shinn, F. Underwood and G. Hahn. General Electric Co., Schenectady, N.Y., Report No. 65-C-118, November, 1965

A basic test procedure was established by which accurate reliability information may be gathered for digital fluid amplifiers. Observations based on preliminary data are as follows: (1) Failures appeared to be nonrandom; failure rates varied with time. (2) Data from some (but not all) test vehicles suggest a higher failure rate under increased temperature. Further, there is no clear cut evidence that pressure or contamination lead to any changes in mean time to failure or that residual effects from previous stress conditions exist. (3) A substantial variability existed in the number of failures between test vehicles.

3. "Reliability Testing of Laminar Jet Fluidic Elements", W. Westerman, Jr. and R. Wright, McDonnell Douglas Astronautics Co., Titusville, FL for Harry Diamond Laboratories, Washington, D.C., Report No. L0266, June, 1974

An evaluation of results from testing laminar jet fluidic elements is presented and compared to performance of turbulent elements. A comprehensive photographic presentation of contamination buildup is included. The test program encompassed a total of 24 elements investigated of which 16 were proportional and 8 were bistable.

4. "Reliability Data for Fluidic Systems with Addendums", W. Fleming and H. Gamble, AiResearch Manufacturing Company of Arizona, Phoenix, AZ for Harry Diamond Laboratories, Adelphi, MD, Report No. HDL-CR-76-092-1, Dec, 1976

An analysis of fluidic control failures experienced during laboratory and experimental testing revealed that the failure mode of greatest concern, fluidic circuit contamination, did not represent a serious obstacle to seeking operational applications for fluidic controls. Production components analyzed include the G.E. thrust reverser actuator on the DC-10 and A.300B Airbus, and other components in various applications.

5. "Flight Control System Reliability and Maintainability Investigations", John Zipperer, et al, Bell Helicopter company; Fort Worth, TX; prepared for U.S. Army Air Mobility R&D Laboratory, Fort Eustis, VA, USAAMRDL-TR-74-57, March 1975, AD-A012233

State of the art for fly-by-wire and fluidic flight control systems and components is reviewed and specific recommendations are made for future R&D efforts necessary to define quality of design and quality of conformance requirements with emphasis on reliability and maintainability. The section on fluidic flight control systems reviews existing documentation describing fluidic systems and comparisons are made with similar fly-by-wire and mechanical systems and components.

6. "Static Test Performance Characteristics of Several Fluidic Control Valve Configurations", T.A. Street, et al, Army Missile Command, Redstone Arsenal, AL, AD-768-772, Sept 1973

Static tests were conducted on seven fluidic valve configurations. Plenum pressures were varied from 500 to 1500 psia with the design pressure being 1200 psia. Recorded data on forces, moments, internal static pressures, and valve exit total pressures are presented.

7. "Roll-Axis Hydrofluidic Stability Augmentation System Development", D. Bengtson, et al, Honeywell, Inc., Minneapolis, MN for U.S. Army Air Mobility R&D Laboratory, Fort Eustis, VA, USAAMRDL-TR-75-43, Sept 1975, AD-A016932

Flight test evaluations of a roll-axis Hydrofluidic Stability Augmentation System (HYSAS) for the OH-58A helicopter are presented. The system operates in conjunction with a previously developed yaw axis HYSAS, and when used with the yaw axis system provided increased vehicle damping and improved handling characteristics.

8. "Program for the Critical Components of a Fly-By-Tube Backup Flight Control System", W.M. Posingies, Honeywell Inc., St. Louis Park, MN for Aircraft and Crew Systems Technology Directorate, Naval Air Development Center, Warminster, PA, NADC Technical Report 77197-60, Jan 1979, AD-A070387

Results of a program to develop an input transducer and summing network for a fly-by-tube system are presented. The concept using signal levels up to +400 psid is accurate, linear, relatively insensitive to changes in fluid viscosity and has a stable null with adequate response.

9. "Electro/Hydraulic/Fluidic Direct Drive Servo Valve", L. Biafore and B. Holland, Columbus Aircraft Div., Rockwell International, Columbus, Ohio for Naval Air Development Center, Warminster, PA, Technical Report 78033-60, March 1979, AD-A069798

The feasibility of providing a fluidic back-up control for the Advanced Flight Control Actuation System (AFCAS) was investigated, potential design concepts evaluated, and technical data and supplier hardware reviewed. A design concept for an electro/hydraulic/fluidic servo valve was selected and a preliminary specification proposed. Fluidic back-up system general requirements are presented.

10. "Flight Test of a Honeywell, Inc. Fluidic Yaw Damper", John Kidwell, Bell Helicopter Co., Fort Worth, TX, for U.S. Army Aviation Material Labs, Fort Eustis, VA, USAAVLABS Technical Report 68-53, July 1968

Flight tests were conducted to evaluate the performance and feasibility of a fluidic yaw damper system which was fabricated for a UH-1C helicopter. Tests encompassed 8.5 flight hours and 2.9 hours of ground and hanger tests. Test results are discussed.

11. "Contamination Effects in a Laminar Proportional Amplifier", R. Comparin, H. Moses and E. Rowell, Virginia Polytechnic Institute and State University, Blacksburg, VA for Harry Diamond Labs, Washington D.C., HDL-TR-175-1, June 1974

A laminar proportional amplifier was tested with a contaminated power supply to determine the nature and location of contaminant deposits and their effect upon the performance of the device. Results show that contamination can cause changes in gain, pressure recovery and null point. A summary of other results is presented together with some geometrical changes to reduce the sensitivity to contamination.

12. "Fluidic Reliability Program", W.J. Westerman and R.E. Wright, McDonnell Douglas Corp, Titusville, FL, for Harry Diamond Laboratories, Washington, D.C. McDonnell report No. L0242, Dec 1973

This report describes work performed to develop an accelerated testing method and a method of predicting life of fluidic systems. Experiments to determine degrading effects of supply gas contamination on fluidic system performance were conducted and noise, frequency, output signal amplitude and gain were monitored. An equation was developed relating fluidic circuit life to the independent variables of contaminant rate, supply pressure, contaminant size, contaminant hardness, nozzle area and element type.

13. "Evaluation of Electro-Fluidic Control Valve", L. Biafore and D. Magnacca, Rockwell International, Columbus, Ohio; prepared for Naval Air Development Center, Warminster, PA. NADC 79077-60, March 1981

The feasibility of providing fluidic backup control of a fly-by-wire actuator was demonstrated in the laboratory. Lab testing demonstrated that the concept will provide satisfactory performance for flight testing in the T-2C Technology Demonstrator aircraft.

14. "Flight Test Evaluation of the Three-Axis Mechanical Stability Agumentation System", G. Fosdick, U.S. Army Air Mobility Research and Development Laboratory, Fort Eustis, VA, December, 1970

A mechanical stability augmentation system using vortex valve fluidic servoactuator was flight tested to evaluate augmentation of stability and control characteristic of a UH-1H helicopter.

15. "U.S. Army Helicopter Hydraulic Servocylinder Reliability and Maintainability Investigation", James Huffman, et. al, Systems Associates, Inc., Long Beach, CA, prepared for Army Air Mobility R&D Laboratory, Fort Eustis, VA, AD-767243, May 1973

An investigation was carried out to identify, isolate, and verify the causes of problems with servo controlled hydraulic actuators used on U.S. Army helicopters, and to trace the resulting effects on helicopter availability. Design requirements, quality assurance provisions, maintenance procedures and practices, test requirements, and procurement practices were analyzed to assess their impact upon the current problems.

16. "A Three-Axis Fluidic Stability Augmentation System", Harvey Ogren, Honeywell, Inc., Minneapolis, Minn., prepared for U.S. Army Air Mobility R&D Laboratory, Fort Eustis, Va, AD739559, Oct 1971

This report covers the analysis, design, fabrication and laborataory tests of a three-axis hydrofluidic stability augmentation system for a UH-1 type helicopter. The system was subjected to temperature and vibration flightworthiness tests. Final tests conducted were closed-loop performance checks using an analog computer to simulate aircraft dynamics.

17. "Three-Axis Fluidic Stability Augmentation System Flight Test Report", M. Ebson, H. Ogren and D. Sotanski, Honeywell, Inc., Minneapolis, Minn., prepared for U.S. Army Air Mobility R&D Laboratory, Fort Eustis, VA, AD-734343, Sept 1971

This report covers the flight test of a three-axis hydrofluidic stability augmentation system for a UH-1 type helicopter. Flight testing results including problems encountered and modifications incorporated during the flight test are discussed.

18. "Development of a Hydrofluidic Stabilization Augmentation System (HYSAS) for an AX Class Aircraft", H.C. Kent, Honeywell, Inc., Minneapolis, Minn., prepared for Air force Flight Dynamics Laboratory, Wright-Patterson AFB, Ohio, AD-A011727, Jan 1975

This report describes a system analysis which included a computer simulation of the Fairchild A-10. From this simulation, a fluidic yaw damper system was fabricated and close-loop tested using the analog computer aircraft dynamic simulation coupled with the yaw damper system mounted on a servoed rate table. Fifteen flight conditions were simulated with the use of the fluidic HYSAS.

19. "Hydrofluidic Servoactuator Development", H. Kent and J. Sjolund, Honeywell, Inc., Minneapolis, Minn., prepared for U.S. Army Air Mobility R&D Laboratory, Fort Eustis, VA, AD-766308, May 1973

This report covers the design and development of a hydrofluidic servoactuator. The servoactuator utilizes a hydrofluidic amplifier cascade input stage which replaces the bellows-flapper-nozzle of a conventional servovalve, a fluid feedback transducer, and an actuator. Testing results are discussed.

20. "Weight Assessment of a 3 Axis Fluidic Backup Flight Control System", Robert Olesen, Vought Corp. Dallas Texas, Report No. 2-51700-C/IR-52688, March 1981

This report addresses the question of the weight incurred with the fluidic backup system and makes a comparison of the weight associated with competitive backup control system such as mechanical or analog electronic.

21. "Development of a Control Air Supply Filtration System", Michael Cycon, AiResearch Manufacturing Co., Final Report N00019-78-C-0393, October 1979, prepared for Naval Air System Command, Washington, D.C.

This report presents the results of a program to design and fabricate a two-stage pneumatic filter using a cyclones separator as the first stage and a conventional wire mesh surface media filter as a second stage. Test results are discussed.

22. "Three-Axis Fluidic/Electronic Automatic Flight Control System Flight Test Report", L.S. Cotton, United Aircraft Corporation, AD/A-000 894, August 1974, prepared for Army Air Mobility R&D Laboratory Fort Eustis, VA

This report covers the flight test of a three-axis hydrofluidic SAS coupled with a completely independent parallel attitude and heading hold for a CH-54B helicopter. Problems during the test phase are discussed.

23. "The Design, Fabrication, and Test of an Electrofluidic Servovalve", M. Funke and L. Pecan, Tritec, Inc., Columbia, MD, prepared for Applied Technology Laboratory, AVRADCOM, Fort Eustis, VA, AD-A082443 February, 1980

This report includes test results of a dual input servovalve using fluidic amplilfiers and postive derivative feedback. Components tested included torque motor, amplifiers, spool and actuator.

24. "Reliability of Aerospace Fluidic Controls", J.M. Mix, AirResearch Manufacturing Co., Phoenix, Arizona, prepared for presentation at the 1972 ASME Winter Annual Meeting, N.Y.

This report discusses various experiments on fluidic circuits and associated problems encountered with contaminants.

25. "Hydrofluidic Component and System Reliability", L. Banaszak, Honeywell, Inc. Minneapolis, MN, prepared for presentation at the 1972 ASME Winter Annual Meeting, N.Y.

Tests which define drift-type failure modes are discussed.

26. "Evaluation of Electrofluidic Control Valve", L.P. Biafore and D.A. Magnacca, Rockwell International, Columbus, Ohio and David Keyser, Naval Air Development Center, Warminster, PA, NADC Report 79077-60, March 1981.

27. "Fluidic Backup Flight Controls, a Feasibility Study", Robert Woods, Vought Corporation, Dallas, TX, prepared for Naval Air Systems Command, Washington, D.C., Report No. N00019-78-C-0460, June 1979.

This report includes a comprehensive survey of the current state-of-the-art in fluidic technology applicable to flight control systems, configurations of a backup flight control system and predictions for the performance and reliability of a fluidic system.

28. "Hydrofluidic Fly-by-Tube Primary Flight Control System", R. F. Helfinstine and H.C. Kent, Honeywell, Inc., St. Louis Park, MN, prepared for Naval Air Systems Command, Washington, D.C. Final Report 41-2745, August 1980.

This report describes the program to test and evaluate the operational readiness of three Air Research fluidic components. Cyclic endurance tests, vibration endurance tests and performance tests were conducted on each component. Test results are discussed and problem areas associated with long - time use of fluidic components are discussed.

30. "Two-Stage Servovalve Development Using a First-Stage Fluidic Amplifier", Richard Deadwyler, Harry Diamond Laboratories, Adelphi, MD, HDL-TM-80-21, July 1980.

This report describes research on two-stage hydraulic servovalves (torque motor, flapper nozzel valve) and first-stage fluidic amplifiers.

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